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Implications of a possible clustering of highest-energy cosmic rays

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ABSTRACT **Recently, a possible clustering of a subset of observed ultra-high energy cosmic rays above $\simeq$40 EeV (4 $\times$ 10^{19} eV) in pairs near the supergalactic plane was reported. We show that a confirmation of this effect would provide information on the origin and nature of these events and, in case of charged primaries, imply interesting constraints on the extragalactic magnetic field. Possible implications for the most common models of ultra-high energy cosmic ray production in the literature are discussed.**

The recent detection of ultra-high energy cosmic rays (UHE CRs) with energies above 100 EeV (1–5) has triggered considerable discussion in the literature on the nature and origin of these particles (6–8). On the one hand, even the most powerful astrophysical objects such as radio galaxies and active galactic nuclei are barely able to accelerate charged particles to such energies (9). On the other hand, above $\simeq$70 EeV, the range of nucleons is limited by photopion production on the cosmic microwave background to about 30 Mpc (10, 11), whereas heavy nuclei are photodisintegrated on an even shorter distance scale (12). In addition, for commonly assumed values of the parameters characterizing the galactic and extragalactic magnetic fields, protons above 100 EeV are deflected by only a few degrees over these distances (6).

Currently there exist three classes of models for UHE CRs. The most conventional one assumes first-order Fermi acceleration of protons at astrophysical magnetized shocks (see, e.g., ref. 13). This mechanism is supposed to be associated with prominent astrophysical objects such as active galactic nuclei and radio galaxies. One problem with this scenario is that no obvious candidate could be found within a cone around the arrival direction of the two highest-energy events observed whose opening angle is given by the expected proton deflection angle (4, 7).

Recently, a second class of models has been suggested; namely, that UHE CR could be associated with cosmological gamma ray bursts (GRBs) (14–16). This was motivated mainly by the fact that the required average rates of energy release in γ-rays and UHE CRs above 10 EeV turn out to be comparable. Protons could be accelerated beyond 100 EeV within the relativistic shocks associated with fire ball models of cosmological GRBs (17–19). Because the rate of cosmological GRBs within the field of view of the cosmic ray experiments that detected events above 100 EeV is about 1 per 50 years (yr), a dispersion in UHE CR arrival time of at least 50 yr is necessary to reconcile observed UHE CR and GRB rates. Such a dispersion could be caused by the time delay of protons due to magnetic deflection (14, 20).

The third class of models are the so-called "top-down" (TD) models. There, particles are created at UHEs in the first place by the decay of some supermassive elementary "X" particle associated with possible new fundamental particle physics near the grand unification scale (21). Such theories predict phase transitions in the early universe that are expected to create topological defects such as cosmic strings, domain walls, or magnetic monopoles. Although such defects are topologically stable and would be present up to today, they could release X particles due to physical processes such as collapse or annihilation. Among the decay products of the X particle are jets of hadrons. Most of the hadrons in a jet (of the order of 10^4–10^5) are in the form of pions that subsequently decay into γ-rays, electrons, and neutrinos. Only a few percent of the hadrons are expected to be nucleons (22). Typical features of these scenarios are thus the predominant release of γ-rays and neutrinos, and spectra that are considerably harder than in the case of shock acceleration. For more details about these models, see, e.g., ref. 23.

Quite recently, a possible correlation of a subset of events above 40 EeV among each other and with the supergalactic plane was reported by the Akeno Giant Air Shower Array (AGASA) experiment (24). Among 20 events with energy above 50 EeV, two pairs of events with an angular separation of less than 2.5° were observed within 10° of the supergalactic plane that approximates the large-scale structure of galaxies within a few tens of Mpc from us. For an underlying isotropic, unclustered distribution of sources, this corresponds to a chance probability of $\simeq 4 \times 10^{-4}$. A third pair was observed among 36 showers above 40 EeV, with a corresponding chance probability of about 6×10^{-3}. The events within one pair, therefore, may instead have been emitted by a single, discrete source possibly associated with the large-scale structure. The deflection angle of a charged particle in a magnetic field is inversely proportional to its energy E. Therefore, the fact that the lower energy event in the pair with the greatest energy difference (51 EeV and 210 EeV) arrived later suggests that it might have been produced in a burst (i.e., on a time scale $\lesssim$1 yr) and the time delay is dominated by magnetic deflection of the (charged) lower-energy particle. Even the two other pairs observed by AGASA could be consistent with production in a burst if at least the higher-energy particle that arrived later was deflected, because the dispersion of the delay time due to magnetic deflection can be comparable to its average, which is $\propto E^{-2}$ (see below). Furthermore, the distance to the source cannot be much larger than $\simeq$100 Mpc if the higher-energy primary was either a nucleon, a nucleus, or a γ-ray, because its energy was observed to be $\gtrsim$75 EeV in all three pairs.

In this paper we investigate possible consequences of a confirmation of the above-mentioned scenario of bursting sources suggested by the AGASA results. In section 2 we discuss consequences for the strength and structure of the galactic and extragalactic magnetic fields. In section 3, implications for the different classes of UHE CR models currently discussed in the literature are addressed. We summarize our

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Abbreviations: UHE, ultra-high energy; CR, cosmic ray; GRB, gamma ray burst; TD, top-down; EGMF, extragalactic magnetic field; yr, year; AGASA, Akeno Giant Air Shower Array.

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findings in section 4. Throughout the paper we use natural units with $c = \hbar = 1$.

Magnetic Field Constraints from Time Delay and Deflection

Let us assume that the extragalactic magnetic field (EGMF) can be characterized by a typical field strength B and a coherence length scale l_c. Over distances $r < l_c$, a relativistic particle of energy E and charge e will then be deflected by an angle $\alpha = r/r_l$, where $r_l = E/eB$ is the Larmor radius. A random walk over distances $r > l_c$ leads to an rms deflection angle $\alpha_{\rm rms} = (2r/9l_c)^{1/2} l_c/r_l$, if energy loss is negligible over this distance (25). The average time delay caused by these deflections is then given by ref. 25

$$\tau_E = \frac{\alpha_{\rm rms}^2 r}{4} = 1.5 \times 10^3 \left(\frac{E}{100\mathrm{EeV}}\right)^{-2} \cdot \left(\frac{r}{10\mathrm{Mpc}}\right)^2 \left(\frac{B}{10^{-9}\mathrm{G}}\right)^2 \left(\frac{l_c}{1\mathrm{Mpc}}\right) \mathrm{yr}. \quad [1]$$

For the actual distribution of time delays one has to distinguish two cases: If $\alpha_{\rm rms} \ll l_c/r$, all particles "see" the same magnetic field configuration while propagating over the distance r. Therefore, the distribution peaks around τ_E with a dispersion of, at most, a few percent (25). Conversely, if $\alpha_{\rm rms} \gg l_c/r$, the dispersion is comparable to the average, and the distribution $p_E(t)$ of time delays at the given energy E is (25)

$$p_E(t) = \frac{\pi^2}{3\tau_E} \sum_{n=1}^{\infty} (-1)^{n+1} n^2 \exp\left(-\frac{\pi^2 n^2 t}{6\tau_E}\right). \quad [2]$$

The above generally applies for $E \lesssim 50$ EeV, where photopion production and, therefore, energy loss is negligible over the distance to the supposedly common source of the events constituting a pair. At higher energies, the distributions cannot be strictly derived analytically but are usually determined from Monte Carlo simulations (26–28). The following approximate expression was given in ref. 29 for the photopion production regime and $r \gg l_c$:

$$p_E(t) = \frac{\beta}{3\beta/4 + 1} \frac{1}{\tau_E} \times \begin{cases} \frac{4}{3}\Theta(t/\tau_E - 1/4)(t/\tau_E - 1/4) & \text{for } t < \tau_E \\ (t/\tau_E)^{-\beta-1} & \text{for } t > \tau_E \end{cases}, \quad [3]$$

where the power law tail $\propto t^{-\beta-1}$ for $t \gg \tau_E$, with $\beta \simeq 1$ approximates the influence of strong magnetic field regions, for example, in galaxy clusters.

For a bursting source, the integral distribution of delay times $t_1 - t_2$ between events of energy $E_1 < E_2$ is then given by

$$P(t_1 - t_2) = \int_0^{t_1 - t_2} dt' \int_0^{\infty} dt p_{E_1}(t) p_{E_2}(t - t'). \quad [4]$$

Thus, the probability to detect an event of energy $E_1 < E_2$ within a time $t_1 - t_2$ after an event of energy E_2 has been detected is roughly given by the product of Eq. **4** with the ratio of integral fluxes at these energies, $F(E_1)/F(E_2)$. For sources nearer than $\simeq$100 Mpc (for $E_2 \lesssim 80$ EeV) or $\simeq$30 Mpc (for $E_2 \lesssim 200$ EeV), $F(E)$ can roughly be taken as the unmodified injection flux, which we assume to be $\propto E^{-\gamma}$, with $\gamma \lesssim 1$. To allow for the most general case, we computed Eq. **4** for a given τ_E, adopting for $p_{E_1}(t)$ and $p_{E_2}(t)$ any of the three distributions discussed above that is relevant for substantial or negligible energy loss and/or for $\alpha_{\rm rms} \ll l_c/r$ or $\alpha_{\rm rms} \gg l_c/r$, for all three pairs. Under the assumption of bursting sources, at least the pair in which the lower energy event arrived later implies $\tau_{100\ \mathrm{EeV}} < 5$ yr to about 95% confidence level. By use of Eq. **1**, this translates into the following constraint on the EGMF:

$$B \lesssim 2 \times 10^{-11} \left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{-1/2} \left(\frac{r}{30\ \mathrm{Mpc}}\right)^{-1} \mathrm{G}, \quad [5]$$

with a corresponding angular deflection much smaller than the angular resolution of about 1.6°. Although we only presented a qualitative analytical argument here to arrive at this tentative constraint, a much more detailed likelihood analysis confirms Eq. **5** for at least two of the three pairs and shows its consistency with the third pair even when the assumption of bursting sources is not made (28). To firmly establish such constraints, more statistics and a confirmation of the assumptions about the sources made here are needed. Note that for a continuously emitting source the difference in arrival times could be source-intrinsic, in which case we can only impose the constraint $\alpha_{\rm rms} \lesssim 2.5°$, leading to the less stringent constraint

$$B \lesssim 5 \times 10^{-10} \left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{-1/2} \left(\frac{r}{30\ \mathrm{Mpc}}\right)^{-1/2} \mathrm{G}. \quad [6]$$

The constraints in Eq. **6** and, in partiuclar, Eq. **5** for bursting sources are considerably more stringent than the existing upper limit on a coherent, all-pervading field of 10^{-9} G, coming from Faraday-rotation measurements (30). If the charged particle would be produced as a heavy nucleus, the bounds in Eqs. **5** and **6** would become even stronger by at least the atomic number of the arriving nucleus, which, due to photodisintegration in the cosmic microwave background, is less than or equal to its original charge.

If observed galactic magnetic fields cannot be explained by a galactic dynamo (31), one might expect protogalactic fields of strength $10^{-12} - 10^{-9}$ G with a coherence scale of order 1 Mpc, depending on the way this field is compressed during galaxy formation (32). A bound such as Eq. **5** would then considerably constrain such a scenario. An all-pervading field would have to be $\lesssim 10^{-11}$ G, whereas stronger fields could not permeate intergalactic space uniformly. Correlations between UHE CR events might therefore offer a means to constrain the EGMF in a way that is complementary to other recently suggested methods (33, 34).

In case of bursting sources, we can thus assume that the observed deflection is dominated by the galactic magnetic field. If we assume this field to be coherent over a scale l_g, its strength being B_g, we obtain for $E = 50$ EeV

$$\alpha \simeq 1.1° Z \left(\frac{l_g}{1\ \mathrm{kpc}}\right) \left(\frac{B_g}{10^{-6}\mathrm{G}}\right) \sin\theta, \quad [7]$$

for a nucleus of charge Ze, where θ is the angle between the field polarization and the arrival direction of the particle. In addition, from $\tau_E \simeq \alpha^2 l_g/2$, a time delay of $\simeq$2 yr can be explained if $l_g \simeq 1(\alpha/2°)^2$ kpc, at least for the pair at which the lower energy event arrived later. These numbers are quite consistent with observational knowledge on the galactic magnetic field parameters, $l_g \simeq$ hundreds of pc, $B_g \simeq 3 \times 10^{-6}$ G (35). Furthermore, the observed polarization of the coherent component of the galactic field predicts the arrival directions of lower-energy protons to be of lower galactic latitude than the ones of the higher-energy particle (6). Within the experimental angular resolution this is consistent with the pairs observed by AGASA. Finally, for standard values of the galactic magnetic field parameters, Eq. **7** shows that it is unlikely that the clustered events have been caused by heavy nuclei, with Z greater than a few, because their relative deflection would typically be too large (36).

Implications for Ultra-High-Energy Cosmic Ray Production Scenarios

It was mentioned that two of the three pairs observed by AGASA lie within $\simeq 10°$ of the supergalactic plane. That seems to suggest an origin in some conventional sources associated with the large-scale structure such as powerful galaxy clusters or active galactic nuclei. Because no such object was identified as an obvious source, the situation with regard to conventional shock acceleration models remains inconclusive at the present time. It has also been noted recently (37) that a strong concentration of UHE CRs toward the supergalactic plane would be inconsistent with a correlation with the known large-scale structure.

This raises the question about the perspectives of alternative models to explain possible correlations between events with energy slightly below and above 60 EeV. In this energy range, the most readily detectable particles are γ-rays and nucleons whose range is limited to less than $\simeq 100$ Mpc (see, e.g., ref. 38). The AGASA experiment is approximately sensitive to a cone with opening angle $\simeq 45°$ around the zenith. For $\tau_{100\ \mathrm{EeV}} \gtrsim 1$ yr, the rate of bursts f_b causing the observed pairs must obey $f_b \sim 3.2 \times 10^{-7}\ (\tau_{100\ \mathrm{EeV}}/5\ \mathrm{yr})^{-1}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$. The combined integral flux above 100 EeV from Fly's Eye (2) and AGASA (5) is $J(100\ \mathrm{EeV}) \simeq 5 \times 10^{-21}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$. From this, we can obtain a rough estimate of the necessary energy release per burst, $E_b \simeq 4\pi E J(E)/\lambda(E) f_b \simeq 3 \times 10^{50}\ (\tau_{100\ \mathrm{EeV}}/5\ \mathrm{yr})$ erg, where we used $E = 100$ EeV, and $\lambda(E) \simeq 30$ Mpc is the attenuation length of the particle species dominating the observed flux.

In relativistic fire ball models of GRBs the time scale for proton acceleration is limited by the dissipation radius $r_d \lesssim \gamma_b^2 t_\gamma \lesssim 2.9 \times 10^{-3}\ (\gamma_b/300)^2$ yr, where γ_b is the Lorentz factor of the expanding fire ball and $t_\gamma \sim 1$ s is the observed duration of the (low-energy) γ-ray burst. Thus, in these models the release time scale of UHE CRs is indeed short compared with the time delay in the observed pairs. However, the rate of cosmological GRBs, $f_\gamma \simeq 3 \times 10^{-8}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$ (39), would be in conflict with the rate f_b if $\tau_{100\ \mathrm{EeV}} \ll 50$ yr (14), as suggested by the pairs observed by AGASA. Confirmation of typical time delays in clustered events as small as a few years would thus most likely rule out this type of cosmological GRB model as an explanation for such clusters. This is in analogy to the fact that confirmation of recently claimed positional coincides between highest-energy cosmic rays and strong GRBs (16) would rule out an origin of UHE CRs in cosmological GRBs. An association of UHE CRs with GRBs would then at best be possible if GRBs were situated in the galactic halo (40), an option that might soon be ruled out by an increasing data set on GRBs.

Let us now turn to the hypothesis that the bursting sources consist of topological defects. For example, certain classes of cosmic string loops might collapse and release all of their energy in form of UHE CRs within about one light-crossing time t_b (41). If v is the symmetry-breaking scale associated with the phase transition in which the string was formed, $t_b \simeq 13\ (E_b/3.1 \times 10^{50}\ \mathrm{erg})(v/10^{23}\ \mathrm{eV})^{-2}\ \mathrm{s} \ll 1$ yr, and thus the "burst condition" is fulfilled.

What remains to be discussed is the UHE CR composition predicted by TD models. We have recently performed extensive numerical simulations for the propagation of extragalactic nucleons, γ-rays, and electrons with energies between 10^8 eV and 10^{25} eV through the universal low-energy photon background (42). All relevant interactions have been taken into account, including synchrotron loss in the EGMF of the electronic component of the electromagnetic cascades, which result from UHE γ-ray injection into the universal radiation background. Here, we assume an EGMF of 10^{-12} G, which

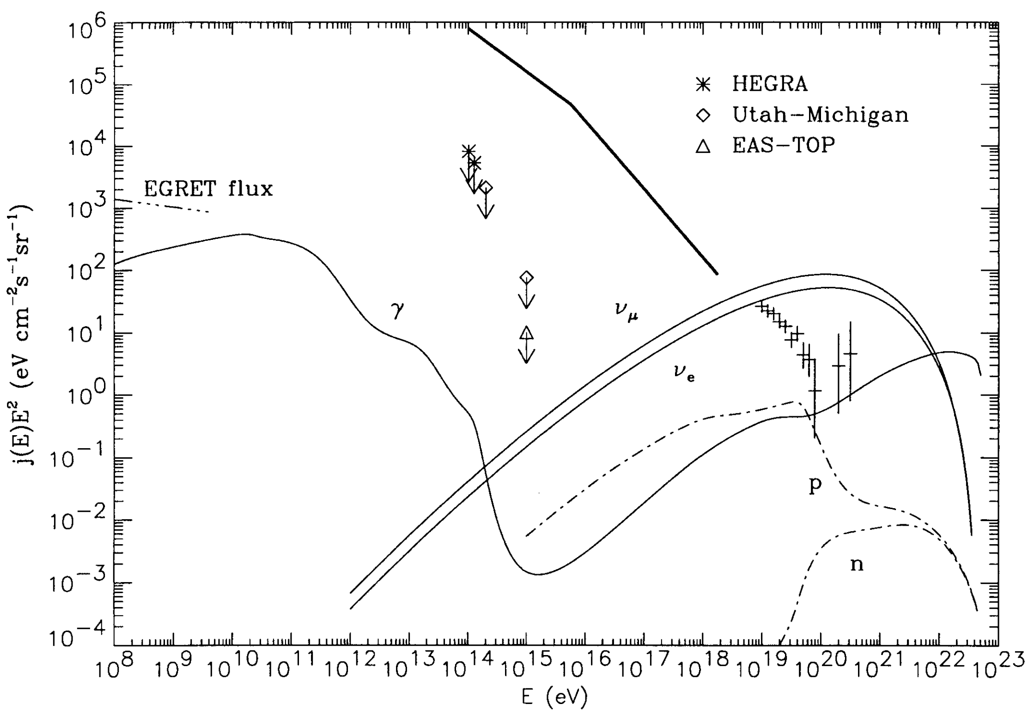

FIG. 1. Predictions for the time-averaged differential fluxes of γ-rays, protons, and neutrons above 10^{15} eV and $\nu_\mu + \bar{\nu}_\mu$, $\nu_e + \bar{\nu}_e$ by a typical TD scenario. About 3% of the total energy is injected as nucleons, 30% as γ-rays, and the rest as neutrinos with a spectrum roughly $\propto E^{-1.5}$ up to $E = 10^{23}$ eV (for more details about the model and the simulations, see ref. 42). The average EGMF strength was assumed to be 10^{-12} G. Also shown are the combined data from the Fly's Eye (1, 2) and the AGASA (5) experiments above 10 EeV (data with error bars), piecewise power-law fits to the observed charged CR flux (thick, solid line), and experimental upper limits on the γ-ray flux at 0.1–5 GeV from Energetic Gamma Ray Experiment Telescope (EGRET) data (48) (dashed–dotted line along left margin). Points with arrows represent upper limits on the γ-ray flux from the High-Energy Gamma Ray Astronomy (HEGRA) (49), the Utah–Michigan (50), and the Extensive Air Shower Experiment at Campo Imperatore (EAS-TOP) (51) experiments, as indicated.

obeys the constraint from Eq. **5**. Time-averaged predictions from a representative TD model are shown in Fig. 1. Because for the burst rates suggested by the clustering observed by AGASA at any time, roughly one burst contributes to the flux above a few tens of EeV, the UHE fluxes at these energies are representative for a typical burst induced by a topological defect at a distance $\simeq$50–100 Mpc. The flux normalization was optimized to allow for an explanation of the highest-energy events observed and corresponds to a likelihood significance for this fit of $\simeq$0.95 above 100 EeV (for details, see ref. 43). The flux below a few tens of EeV is presumably produced by conventional shock acceleration. It can clearly be seen that the scenario shown in Fig. 1 is consistent with current data and bounds on γ-ray and UHE CR fluxes. For more details on constraints on TD models, see refs. 42 and 44. Fig. 1 shows that events above $\simeq$80 EeV are predicted to be most likely γ-rays, whereas around 50 EeV an approximately equal amount of protons is expected from the TD-induced bursts. About one-fifth of the total observed flux at these energies would be due to protons from the TD-induced bursts, in rough agreement with the 2 observed pairs out of 20 events above 50 EeV. Because for a given energy the amount by which an electromagnetic cascade particle (i.e., a γ-ray or an electron) and a nucleon is deflected and delayed is comparable, this scenario is clearly consistent with the discussion of the previous section. We also note that the muon content of the showers observed by AGASA is not in contradiction with interpreting the higher-energy event in the pairs as a γ-ray (24), but improved data on UHE CR composition could rule out the TD hypothesis in the future.

Conclusions

We discussed the consequences of a possible clustering of a subset of UHE CR events above $\simeq$40 EeV, which recently was reported by the AGASA experiment. If the observed time delay of low- relative to high-energy events of $\simeq$2 yr is typical, it could be caused by deflection in magnetic fields, and the correlated events might originate in a burst on a time scale shorter than $\sim$1 yr. If the real angular deviation between clustered events is not much smaller than 1° (which currently cannot be excluded, because the angular resolution of the AGASA experiment is comparable to the observed deviation), deflection of charged particles by the EGMF should be negligible and can be exclusively attributed to the galactic magnetic field, provided the charge is smaller than a few times the proton charge. This would substantially improve existing limits on the EGMF. Scenarios in which the magnetic fields observed in galactic disks originate from an EGMF of strength 10^{-12}–10^{-9} G with coherence length scales of $\simeq$1 Mpc would be constrained considerably. This possibly could indicate that such protogalactic fields cannot be primordial (i.e., permeate all of intergalactic space).

The time delays of $\simeq$2 yr between lower- and higher-energy events in the pairs observed by AGASA might be in conflict with models that associate such events with cosmological GRBs. Conventional shock acceleration models require identification of a prominent astrophysical object as a source candidate within a few degrees of the arrival directions of the events. No obvious identification could be made for the event clusters observed. This might hint to the operation of a TD-type mechanism where part of the UHE events would be related to new, fundamental physics near the grand unification scale. In such a scenario, events below and above $\simeq$80 EeV could be mostly nucleons and γ-rays, respectively, if the EGMF is $\lesssim 10^{-11}$ G and the event pairs observed by AGASA could be produced in bursts on time scales less than $\simeq$1 yr. The burst rate per volume would be somewhat higher with a correspondingly lower energy release per burst than in the cosmological GRB scenario. This possibility currently is not ruled out by any data.

Future instruments in construction or in the proposal stage, such as the Japanese Telescope Array (45), the High Resolution Fly's Eye (46), and the Pierre Auger Project (47), will have the potential to test whether there is significant clustering of UHE CRs. The latter experiment, with an angular resolution of a fraction of 1° and an energy resolution of $\simeq$10%, should detect clusters of the order of 10 or more events if the clustering observed by AGASA is real. This would allow a more detailed statistical analysis of delay times and, thus, EGMF constraints.

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